LA-UR- 12-01729

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Meeting the Challenge for Worker Safety

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Intended for: Fifty-Third Annual Meeting INMM

Los Alamos
NATIONAL LABORATORY
EST. 1943

Los Alamos National Laboratory Overview of the SAVY-4000 Design: Meeting the Challenge for Worker Safety

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Abstract

Incidents involving release of nuclear materials stored in containers of convenience such as food pack cans, slip lid taped cans, paint cans, etc. has resulted in defense board concerns over the lack of prescriptive performance requirements for interim storage of nuclear materials. Los Alamos National Laboratory (LANL) has shared in these incidents and in response proactively moved into developing a performance based storage container design, the SAVY-4000. The SAVY-4000 is the first vented general use nuclear material container demonstrated to meet the requirements of DOE M 441.1-1, Nuclear Material Packaging Manual.

The SAVY-4000 is an innovative and creative design demonstrated by the fact that it can be opened and closed in a few seconds without torque wrenches or other tools; has a built-in, fire-rated filter that prevents the build-up of hydrogen gas, yet retains 99.97% of plutonium particulates, and prevents release of material even in a 12 foot drop. Finally, it has been tested to 500C for 2 hours, and will reduce the risk to the public in the event of an earthquake/fire scenario. This will allow major nuclear facilities to credit the container towards source term Material at Risk (MAR) reduction.

The container was approved for nuclear material storage in the TA-55 Plutonium Facility on March 15, 2011, and the first order of 79 containers was received at LANL on March 21, 2011. The first four SAVY-4000 containers were packaged with plutonium on August 2, 2011. Key aspects of the SAVY-4000 vented storage container design will be discussed which include design qualification and testing, implementation plan development and status, risk ranking methodology for re-packaging, in use implementation with interface to LANMAS, surveillance strategy, the design life extension program as enhanced by surveillance activities and production status with the intent to extend well beyond the current five year design life.

General Information

The Department of Energy (DOE) issued DOE M 441.1-1, *Nuclear Material Packaging Manual*, hereafter referred to as the Manual, in March 2008, to protect workers who handle nuclear material from exposure due to loss of containment of stored materials. The Manual specifies a detailed approach to achieve high confidence in containers and includes requirements for container design and performance, design-life determinations, material contents, and surveillance and maintenance to ensure container integrity over time. The materials considered within the scope of the Manual include actinides stored outside an approved engineered-contamination barrier that could result in a worker exposure of greater than 5 rem Committed Effective Dose Equivalent (CEDE) if containment is lost.

Operational realities within the Plutonium Facility (PF) at Los Alamos National Laboratory (LANL) become relevant when developing design criteria for optimum storage container design. For example, the main storage vault is near capacity and new replacement container designs are limited to the footprint of existing container sizes. Furthermore, with ongoing and expanding missions at LANL (e.g., MOX fuel, Life Extension Programs, Pit Manufacturing Capability, etc.), the container design must demonstrate ease of use to minimize worker exposure, and it must allow a wide variety of contents to minimize costs.

Nuclear Filter Technology, Inc. (NucFil) and LANL developed the SAVY-4000 container as a simple, robust, and reusable container for storing solid nuclear materials. The SAVY-4000 family of containers includes seven sizes (1-, 3-, 5-, 8-, and 12-quart then 5- and 10- Gallon). The design of this container includes a filter to facilitate the release of hydrogen, thus preventing flammable gas mixtures from forming. The filter ensures that only minimal pressure (1 kPa) is possible within the container during use. In this respect, the container is not a pressure vessel but a light weight, worker-friendly container.

The SAVY 4000 container has been designed to meet DOE M 441.1-1, Nuclear Material Packaging Manual, technical requirements. Design considerations include the material allowed, operational temperature, corrosion and gas buildup, drop scenarios and lifetime. The choice of bounding material influences the container lifetime and affects the degradation mechanisms associated with radiation and corrosion. Components of most concern are the filter and O-ring. The radiation dose to these components has been modeled by Monte Carlo methods. We are confident of a five-year lifetime, but extending this to 40 years will require surveillance and laboratory studies. Fire tests show significant material retention which can reduce Material at Risk in nuclear facilities. The effect of flow rate on filter efficiency has also been considered. A Safety Analysis Report has been prepared to support review of the SAVY-4000 quart-size storage container design for DOE M 441.1-1compliance.

Container Description

The SAVY-4000 is a general purpose, reusable container designed for the storage (inside a nuclear facility) of solid nuclear material with a permitted loading of up to 25 watts. The primary reliance on the HEPA filtered nuclear facility to protect public safety in a design basis accident scenario allows the design features of the container to be specifically (but not exclusively) targeted at protecting nuclear workers from both external and internal radiation dose. However, with successful fire testing, the container is credited as Safety Class (protecting public safety) in certain nuclear facility accident scenarios.

The filtered design obviates the need for heavy, pressure vessel type construction or welded closures. One of the main features of the design is its simplicity of operation to minimize external worker dose during handling, while providing protection from internal worker dose through aerosol particulate containment over a relatively long storage period (5 years minimum). Once the container is closed, it provides a credited engineering control, and allows workers to handle the containers without the need for respirator protection. It is light enough for hand carrying, and it protects the worker from accidentally dropping the container from as high as 12 feet. The design also includes a nesting feature such that each container fits inside the next larger size. Figure 1 below shows a SAVY-4000 container with labels identifying each of the primary components. The components of concern are the Viton O-ring, the water resistant membrane, and the ceramic fiber filter

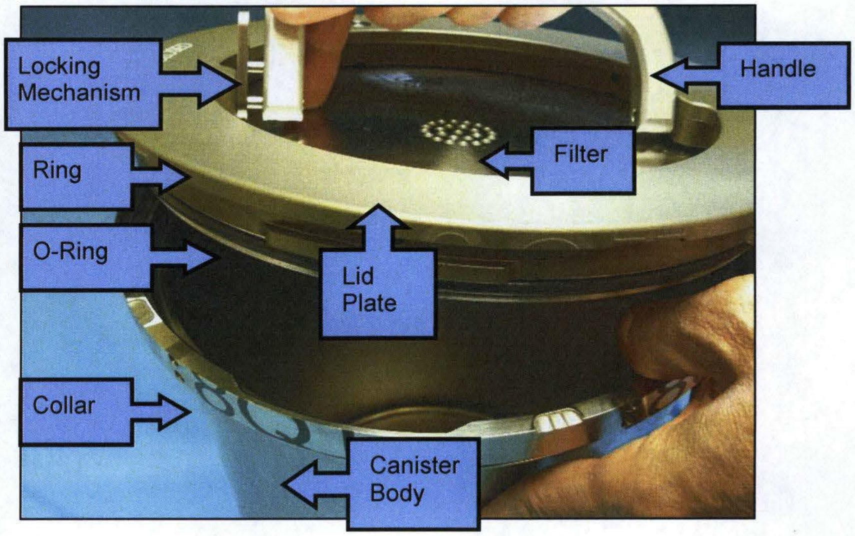


Figure 1. SAVY-4000 Primary Components

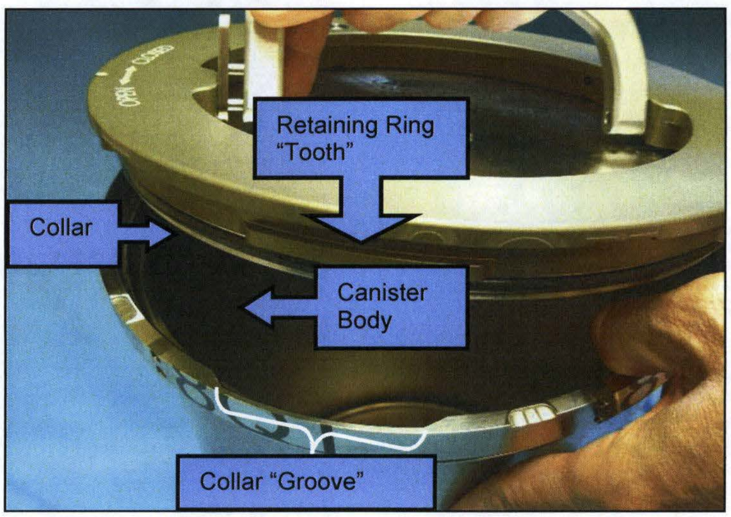


Figure 2. Closure Mechanism

The body and lid are attached to one-another with a bayonet style closure such that the lid fits tightly within a collar attached to the body, Figure 2 above. The user achieves a leak tight seal by pushing the lid downward into the collar resulting in radial compression of the O-ring in a "piston groove" configuration between the body collar and the lid. The lid locks into place with a positive mechanical engagement made of aluminum and a stainless steel pin, and no tools are required to open or close the container. The internal components that form the containment boundary are made of 316L stainless steel for corrosion resistance. The filter is composed of ceramic fibers making it radiation, temperature, and corrosion resistant. The overall primary dimensions and weights of the quart-size and gallon-size containers can be found in

Table **1**.

Table 1. Overall Primary Dimensions and Weights of the SAVY-4000 Container

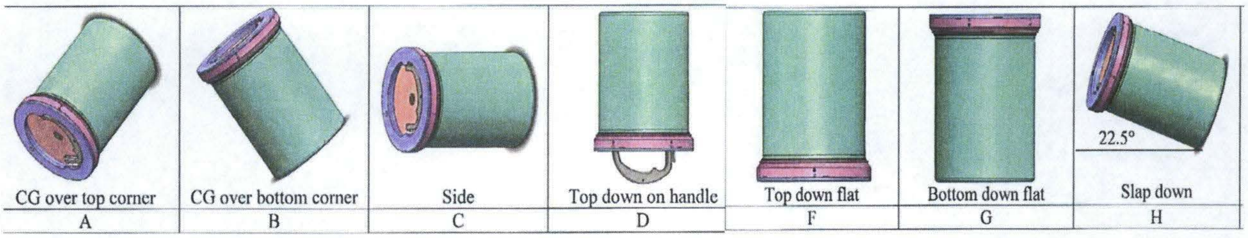
Size	Overall Diameter (cm)	Overall Height (cm)	Inner diameter (cm)	Usable Inner Height (cm)	Gross Weight (kg)	Tare Weight (kg)	Payload Max Weight (kg)
1 qt	12.116	15.189	9.322	11.13	10	1.5	8.5
3 qt	16.637	20.193	13.843	17.17	15	2.5	12.4
5 qt	19.558	25.273	16.764	22.25	18	3.4	14.8
8 qt	22.479	29.083	19.685	26.06	20	4.2	15.7
12 qt	25.400	35.433	22.606	32.41	22	5.4	16.8
5 gal	29.845	39.789	26.035	35.71	25	8.6	16.4
10 gal	39.291	44.793	35.481	40.31	40	11.9	28.0

Design-Release Rate and Design-Qualification Release Rate

The design-release rate is calculated by converting the Manual's value of 10^{-6} A_2 per hour utilizing the approach outlined in Attachment 5 of the Manual. The design-release rate was determined using "Heat Source" plutonium, which is nominally 89% Pu-238. The SAVY-4000 container has a design-release rate of 5.6 x 10-6 cm^3/s of fluid. For calculating the He leak-test criterion, the fluid is assumed to be air at ambient pressure. The design–qualification release rate was calculated by converting the Manual value of 10^{-3} A_2 per ten minutes, utilizing the approach outlined in Attachment 5 of the Manual. The design–qualification release rate was determined using "Heat Source" plutonium, which is nominally 89% Pu-238. The SAVY-4000 container has a design-qualification release rate of 0.034 cm^3/s of fluid. For calculating the He leak-test criterion, the fluid was assumed to be air at ambient pressure.

Design Qualification and Testing

The structural features of the container include a single impact limiting feature designed into the lid to absorb energy in a center-of-gravity over top corner drop orientation. This feature is required to isolate the sealing surfaces of the O-ring from the stresses associated with the impact from a drop. All other components have proven structurally sufficient as demonstrated by drop testing. Qualification was soley by test, dropping in seven different orientations to ensure the worst case was bounded. Phase I egineering evaluation drop tests were successful meeting the more stringent design release rate criteria which is orders of magnitude more stringent than the post drop design qualification release rate the containers actually have to meet with the acception of the 10 Gallon size. The 10 Gallon size had to undergo a slight design change, adding extra structural ribbing to the inside of the lid to pass the test- see drop test results, Figure 3. Phase II testing repeated all drops with production certified containers, again all tests passed the more stringent design release rate criteria.



	PHASE 1		PHASE 2	
Container Size	Pre-drop He Leak Rate Range[1] (x 10^{-7} atm cm^3 s^{-1} @10 kPa)	Post-drop He Leak Rate Range[1] (x 10^{-7} atm cm^3 s^{-1} @10 kPa)	Pre-drop He Leak Rate Range[1] (x 10^{-7} atm cm^3 s^{-1} @10 kPa)	Post-drop He Leak Rate Range[1] (x 10^{-7} atm cm^3 s^{-1} @10 kPa)
1 qt	0.4	0.4 - 3.6	1.9 - 2.5	3.1 - 6.0
3 qt	1.7 - 2.7	4.8 - 7.2	0.8 - 1.0	2.1 - 4.1
5 qt	0.3 - 0.6	0.2 - 0.8	0.5 - 0.8	1.6 - 3.6
8 qt	1.7 - 2.3	2.5 - 7.8	0.3 - 0.7	0.4 - 3.4
12 qt	0.2 - 0.7	0.3 - 2.9	0.5 - 1.0	0.4 - 3.6
5 gal	0.6 - 1.6	5.4 - 6.1	1.1 - 2.7	2.2 - 5.6
10 gal	0.3 - 1.2	0.9 - > 9900	1.1 - 3.7	0.8 - 12

[1]Acceptance criterion = 100 x 10^{-7} atm cm^3 s^{-1} @10 kPa

Figure 3. Drop Test Results

The following synopsis lists the Manual Requirements and Performance Objectives with a brief discussion on how the SAVY-4000 design met the requirement.

Corrosion Resistance

316L stainless steel has been shown to be more resistant to corrosion than 304L. All metal container parts potentially in contact with material are made of 316L. The ceramic filter media is highly resistant to acidic attack. Surveillance and maintenance will be used to identify corrosion issues before they become a problem. The lifetime of the Viton o-ring exposed to acidic gases of HCl and HNO3 demonstrated at least 5 year lifetime.

Thermal Degradation Resistance

The maximum temperature during use was determined using simulated vault storage conditions. Each container was instrumented with a 25 Watt heater. Each size was tested, and the maximum measured temperature was 74°C for the o-ring and 80°C for the ceramic filter. The o-ring polymer was tested at elevated temperatures, and an in-service lifetime at 70°C was estimated in excess of 70 years, which meets the five-year design life. Stainless steel and ceramic filter performance is not expected to be affected at these low temperatures.

Radiation resistance

The MCNP calculations were performed and maximum expected dose rates to the o-ring and filter membrane were found to be 2.9 x 103 and 2.2 x 104 rad yr-1, respectively. Inner surfaces when the inner package fails: 1.2 x 106 rad/year alpha in a 45 micrometer layer. Stainless steel and ceramic materials not expected to be affected by the radiation fields generated by the material.

O-ring made of Viton. Skidmore (WSRC-TR-98-00439) reports "Viton, irrespective of filler or type, can withstand 105 – 106 rads with little or no measurable effect on physical properties and up to 107 rads with moderate effect such as 50% loss of elongation and 50% increase in modulus". Therefore, with inner package intact, a 5 year lifetime is conservative.

Oxidative expansion accommodation

Oxidative expansion is a phenomenon associated with oxidation of plutonium metal. The density difference between metal and oxide is sufficient to rupture containers. Plutonium metal is required to be in a hermetically sealed inner container. Administrative limits were placed on Pu metal for 1 and 3 qt sizes (1.0 kg and 4.5 kg, respectively).

Pressurization

Pressure due to radiolysis of water and changes in atmospheric pressure have been evaluated assuming the filter is plugged to 1% of rated capacity. Pressures are less than 2 kPa. Testing is not required, but surveillance and maintenance testing will be used to verify that filters are not plugged.

Incompatible and pyrophoric materials

Incompatible and pyrophoric materials are not to be stored in these containers.

Filter performance

Filter performance specified:

H2 diffusivity: 2.4 x 10-5 mol H2 s-1 (H2 mol fraction)-1. Minimum flow of 200 ml min-1 at 2.54 cmwater column. Filter efficiency: 99.97% of 0.45 micron aerosol at rated flow with an aerosol density of 65 micrograms liter-1. Prevent water entry up to 30.5 cm of water column. Retain 20% of filter efficiency and flow after 500°C for 2 hours. Testing of 100% of production containers. Filter flow and efficiency were tested after drop and fire test.

Design life

Design specification calls for 5 year component design life. Condition of stainless steel and ceramic filter will be monitored as part of the surveillance and maintenance program. Accelerated aging of o-ring under acidic conditions part of testing protocol.

Container closure

Closure seal specified to 5.6 x 10-6 cm3 s-1 of air at 78 kPa at MAWP. The corresponding He leak rate for an atmospheric pressure of 78 kPa at 10 kPa differential pressure is 1.47 x 10-5 atm cm3 s-1. The criterion for passing is set to 1.0 x 10-5. O-ring seal tested after each drop test as part of design test protocol.

Design Release Rate Performance Objective

See closure. Tested as part of testing protocol.

Design Qualification Release Rate Performance Objective

Drop test from 3.05 m with less than 0.034 cm3 s-1 of air at in internal pressure of 78 kPa and a 1 kPa differential pressure. Each container tested after each drop as part of design test protocol.

Authorized Content Description

The SAVY-4000 design specifications allow for the storage of a wide variety of solid actinide materials. The three bounding criteria are the worst case radioactive material, the maximum heat load, and the chemical and physical forms. Any actinide material can be used that is less hazardous than the bounding case pure Pu-238 oxide when inhaled. A summary of the allowable material contents is given in Table 2.

Table 2. Summary Table of Allowable Material Contents

Content	Bounding Case
Identification and maximum quantity of radioactive material	Heat source plutonium oxide Any actinide material with A_2 quantity in grams greater than heat source plutonium oxide is allowed up to 25 watts or by other existing limits (container weight, criticality , external dose limit)
Maximum heat load	25 watts
Chemical form	Allowed: All materials unless specifically not allowed Allowed with restrictions: metals that can undergo oxidative expansion are required to be in hermetically sealed inner containers Not Allowed: Materials with IDES codes C02, C19, C39, C40, C61, GXX, KXX, LXX, N69, R12, and R59 (X is generic for any number or letter.
Physical form	Allowed: Solids; Prohibited: liquids and gases
Maximum Normal Operating Pressure	Differential pressure across container boundary of 1 kPa for quart-size containers
Maximum payload weight	See Table 1-1

Radioactive Material Identification and Maximum Quantity

For the radioactive characteristics, bounding conditions are defined for the A_2 quantity of material consisting of a mixture of isotopes and for overall wattage. Any actinide material whose A_2 quantity is greater than or equal to the bounding values when packaged in a SAVY-4000 container, results in a Manual compliant container with respect to identification of the radioactive material. The bounding values for the A_2 quantity is determined from the isotopic mix of "Heat Source" Pu-238 material, which is the highest specific activity material commonly used in PF-4. The bounding A_2 quantity is 0.0020 grams. Oxide materials bounded by this value include weapon-grade plutonium, fuel-grade plutonium, power-grade plutonium, and americium.

The maximum decay heat load of 25 watts and the specific activity of the material determine the maximum quantity of radioactive material. For instance, weapons-grade oxide with 2.5 watt/kg is limited to a quantity of 10 kg. For some materials the increase in wattage with time will have to be explicitly calculated, and the initial loading will have to be limited to less than 25 Watts accordingly. Other facility-specific limits for specific locations may apply, for instance a criticality limit may not allow 10 kg of weapons-grade oxide in a single container in the vault. Criticality limits and the material at risk (MAR) limits represent facility-specific limits that apply to locations. Radiation protection requirements may also limit the amount of material based on exposure measurements. Contents were identified by any actinide material meeting bounding A2 value, maximum wattage, and restricting Item Description Codes (IDCs).

Some discussion is warranted on why A2 and Wattage is primary in determining bounding limits for authorized contents rather than relying on mass limits. These values allow Manual requirements that were identified under the design qualification section above to be evaluated.

The other Manual technical design requirements do not need knowledge of isotopic mass limits to be evaluated and defining mass limits does not improve on the ability to perform these evaluations.

In actual practice for operations within the nuclear facility measured calorimetry values include the total wattage and are relied upon to ensure the 25 watt limit is not exceeded. In addition, evaluating container contents against isotopic mass limits would require information we may not have.

Providing a complete evaluation of allowable actinide materials by isotopic mass limits is a huge task and greatly complicates authorized content determinations with no added value. Mass limits are important from a criticality perspective, but again this aspect is handled under facility criticality safety limit approvals based on a work area in a given room or location taking into account all the processes occurring in that location.

Chemical and Physical Form

For the chemical and physical forms of allowed material, bounding cases are defined. There are many chemical forms of actinide materials that need consideration and evaluation. The use of Item Description codes (IDES) to characterize material risk was developed to assist in risk ranking materials for repackaging [Smith et al. 2007]. The IDES code is a required field in LANL's Nuclear Material Control and Accountability (NMC&A) database, currently Local Area Nuclear Materials Accountability Software (LANMAS). The allowed chemical and physical forms build on this approach. Gases (IDES G- codes), liquids (IDES L- codes), and combustible (IDES K- codes) materials are prohibited in a Manual-compliant container. All metal items (IDES M- codes) require hermetically sealed-inner containers such as a Conflate container with copper metal gasket. The remaining IDES codes were evaluated against known materials of concern (see Table 3 in Smith et al. [2007]) lists material-reactivity indices as determined by a DOE-wide panel of subject matter experts. This approach was accepted by DOE and the Defense Nuclear Facility Safety Board (DNFSB) in the form of the DOE Manual Implementation Plan for Rec. 2005-1 (IP) and the DNFSB acceptance of IP, respectively). All materials listed in Table 3 in Smith et al. [2007] with a corrosion index greater than 2.3, a pressure index greater than 2.1, and a pyrophoricity index greater than 2 are not allowed. The oxidative expansion issue is mitigated by requiring metal items packaged into inerted, hermetically sealed inner containers.

Location and Contents Configuration within the Container

The SAVY-4000 container content configuration typically consists of an inner container made of metal, placed into a bag-out bag with a contamination-free external surface. The inner packaging clearly mitigates hazards, but is not required for the container to function, nor is it credited towards worker protection (defense in depth). There are instances when surface contaminated internal packaging occurs, such as when a container's outer surface becomes contaminated and requires immediate placement into the next size up container. Inner packages are classified as hermetically sealed or not. Examples of hermetically sealed inner containers include Conflat containers, SRL Large-Part Containers, FK flanged containers, J-Cans, Aluminum Pressure Cookers, and Copenhagen Pressure Cookers. Metal requires sealing into an inert atmosphere in a hermetically sealed-inner container for storage in a SAVY-4000 container. Examples of inner containers that are not hermetically sealed include stainless steel slip-top cans, tin slip-top cans, paint cans, and tin screw cap cans. Oxide bearing materials or compounds can be placed in either a hermetically sealed or non-hermetically sealed-inner container to be stored in a SAVY-4000 container. Material requiring storage is placed into an appropriate inner container. The inner container is bagged out into a plastic bag-out bag (e.g., PVC, polyethylene, or others). This process results in a contamination-free bag with a bulky stub. A SAVY-4000 container is chosen that will fit the bag and stub. Typically the inner container is not upright so as to allow room for the stub. Since there are no internal parts to the SAVY-4000, items are placed inside in any orientation that will fit. In some cases lead or pewter shielding is placed inside the SAVY-4000 and the inner package is placed within the shielding. There is no required configuration as long as the lid seals and the locking mechanism can be engaged.

Reducing Facility MAR

At Los Alamos there is concern about the Material-At-Risk that may be released to the public during a design basis accident. Los Alamos developed a plan to demonstrate that a container exposed to a bounding worst case set of fire conditions in PF-4 laboratories can retain the majority of the stored material. The fire exposures are a time-temperature exposure based on ASTM E-119/NFPA 251 Standard Test Methods for Fire Tests of Building Construction Materials with a final container temperature of 850 °C, and a direct flame engulfment exposure using 20 liters of kerosene burning within a 1 m2 circular pan and an adjacent flame exposure using 20 liters of kerosene burning within a 1 m2 circular pan. Each container was be subjected to a drop test from a height of 12 feet following the thermal insult tests. A total of (4) four of each container type was exposed to each test condition. The Damage Ration (DR) of each container type was determined based on the ability of the container to retain a simulant material (cerium oxide). The average particle size of the cerium oxide powder was approximately 1 μm.

Based on the fire test results, Los Alamos has been able to reduce the Damage Ratio from 1.0 to 0.01 for material in SAVY-4000 containers. The fire tests were performed by Southwest Research Institute, "Evaluation of Fire-Rated Containers when Exposed to Elevated Temperature and Drop Tested in Accordance with Test Plan Document TA55-PLAN-054, R1" Final Test Report Dated March 22, 2012. The SAVY-4000 is then considered Safety Class (protecting the public) for the fire insult.

Surveillance and Life Extension

Every time a container is unpacked, for access to its material or for maintenance, it exposes workers to radiation hazards, and entails a great expense to the laboratory. The aim of these studies is to certify the SAVY-4000 for use for as long a time period as possible, which will limit exposure and expense. The O-ring elastomer materials are known to degrade under radiation and in oxidizing conditions.

Use Surveillance to evaluate changes with time and under varying conditions for components in service and identify unexpected problems. A surveillance high-level goal is to ensure that the SAVY-4000 containers function properly throughout their service life. Statistical sampling rates from the overall container population have been chose to ensure (1) a high level of statistical confidence of detecting potential problems, if they exist, so they can be mitigated, and (2) a high level of statistical confidence of detecting an aging trend that could indicate a change in performance (to support determination of and/or validation of the container's design life).

Without accelerated aging studies, the identification of degradation trends and mechanisms would be difficult if not impossible in the surveillance program. Therefore, we will undertake detailed and extensive accelerated aging studies of the SAVY-4000 O-rings in order to extend the predicted service life of the O-rings and to supplement the required surveillance program. In order to make sense of the data gathered during surveillance of the containers, local expertise must be developed to integrate experimental aging data with data from field usage to refine the aging estimates as the containers age in real time.

Drivers based on basic attributes of elastomers will drive laboratory studies. It is well known that accelerated aging studies at elevated temperatures can result in predicted lifetimes that are much too long.1 Oxidation processes that dominate at lower temperatures, for instance in-service temperatures, may not be observed at elevated temperatures. Chemical consumption of protective additives can result in rapid polymer degradation and severe decrease in performance over a short time after years of very slow degradation. For these reasons, laboratory oxygen consumption studies of Viton are necessary. Radiation by itself does not appear to be problematic; however, any synergy between radiation and low-temperature oxidation or chemical reaction of the protective additives could result in unexpected short in-service lifetimes. Plans are in place to perform laboratory studies of these potential processes.

An integrated approach that utilizes mechanical, spectroscopic, and thermal testing to form a more complete picture of the degradation process will form the basis of our test methodology. A test plan has been developed to define the testing required to predict the service lifetime of Viton-based O-rings used in SAVY-4000 units. The test plan describes the accelerated aging conditions to be used as well as the measurement techniques and observations that will enable a prediction of the O-ring service lifetime under the conditions expected in SAVY-4000 units. These targeted studies of the specific soft durometer Viton formulation used in SAVY containers will yield more accurate lifetime predictions.

Of key importance is existing evidence for an inverse relationship between the sealing force an O-ring applies and the leak rate through a joint containing it at high pressures, but recent development in the theory of seals notes that the leak rate at low pressures is extremely sensitive to the sealing force. Establishing the relationship between sealing force and leak rate then for a SAVY-4000 will be a key experiment for determining the lifetime of the O-ring.

The laboratory will be performing measurements on O-rings from the surveillance program that are designated for destructive evaluation. The measurements will consist of mechanical testing, thermal properties testing, and spectroscopic measurements. The mechanical testing measurements will comprise Shore M hardness, compression stress relaxometry, compression set, and tensile testing. The thermal testing will consist of either Differential Scanning Calorimetry (DSC) or Thermogravimetric Analysis (TGA). Spectroscopic measurements could consist of several different and allow for chemical characterization of material changes. Combining these three approaches permits a more complete evaluation of the aging characteristics of the O-rings

Ultimately, the O-ring lifetime in the SAVY-4000 unit will be determined by changes in mechanical properties that lead to the failure of the O-ring in the leak test of a SAVY-4000 unit By taking into account the viscous flow of the material under stress, the concentration of agents in the O-ring that may be consumed over the course of its lifetime, the reaction rates of the dominant aging processes, and the relationship between chemical transformation and changes in mechanical properties, we will be able to give a justifiable lifetime for the O-ring under the specified conditions of use.